THE MARS MICROPROBE MISSION: A UNIQUE SOLUTION FOR NETWORK SCIENCE

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Abstract

The second deep-space advanced technology validation mission in NASA's New Millennium Program will demonstrate planetary microprobe technologies. Two microprobes, each consisting of a very low-mass aeroshell and penetrator system, are planned to launch in January 1999 and arrive at Mars in December, 1999. The 3 kg probes ballistically enter the martian atmosphere at ≈ 7 km/s and passively orient themselves to meet peak heating and impact requirements. Upon impacting the martian surface at a velocity around 200 m/s, the probes will punch through the entry aeroshell and separate into a fore and aftbody system. The forebody will reach a depth of 0.3 to 2 meters, while the aftbody will remain on the surface for communications.

Each penetrator system includes a suite of highly miniaturized components needed for future micro-networks: Primary batteries, power electronics, control and data handling microelectronics, telecommunications equipment, an antenna, and a science payload package. This paper will summarize the engineering techniques that will be implemented to provide safe landing and operation of the Mars microprobe in its unique environment. The paper will also summarize some key mission and system design trades, as well as discuss some of the technologies being developed

Introduction

The Mars Microprobe Project objectives are derived from the New Millennium Program's goal to revolutionize NASA's space and earth science programs to achieve exciting and frequent missions in the 21st Century through:

- Reduced development costs through the use of validated technologies and enhanced processes
- Reduced launch costs through lowering spacecraft mass and payload
- Reduced operations costs through greater spacecraft autonomy
- Enhanced scientific capability through the above.

Breakthrough technologies are selected from the existing technology "pipeline" - Consisting of ongoing technology programs of NASA, other government agencies, industry, nonprofit organizations, and academia - and are developed in partnership with these organizations.

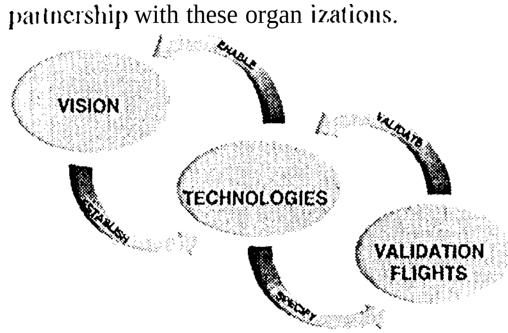


Figure 1: NMP goal diagram,

The author guide uses "Fig. 1" not Figure 1:

These critical technologies will be validated so that future science missions can take advantage of them without assuming the risks inherent in their first use. NMP technology validation flights, to be launched during fiscal years 1998-2000, will also provide opportunities to capture meaningful science data. This NMP goal structure is represented by Figure 1.

In addition to developing and validating key enabling technologies, the NMP will pioneer new ways of partnering with industry, nonprofit organizations, and academic institutions. Further, the development and implementation of the NMP's innovative management practices will advance the competitive edge for NASA and other high-technology organizations.

In particular, the specific objectives for the Mars Microprobe Mission are:

- Demonstrate key technologies which enable future network science missions,
- Demonstrate a passive atmospheric entry and landing system,
- Demonstrate highly integrated microelectronics which can withstand both low' temperatures and high decelerations,
- Demonstrate in-situ, subsurface, science data acquisition and analysis, and
- Provide an opportunity to Collect meaningful science.data,

To demonstrate objectives, the Microprobe Project will develop two probes for deployment at Mars. Upon arrival at the planet, the probes will acquire engineering data during entry, operate the probe. payload, and relay engine.cring and science data to an orbiting spacecraft after impact.

Accommodation Constraints

Due to the unique nature of this mission, the Microprobe Project is subject to various external mission constraints as described below:

First, the probes are a piggy-back payload onboard the 1998 Mars Surveyor Lander spacecraft in January 1999. To minimize the impact on the 1998 Mars Lander, the following agreements have been made:

- Two probes will be mounted on the. Lander stack in a balanced configuration,
- There will be no electrical interfaces between the.probes and the Lander flight system, and
- The probes will not require spin stabilization upon release.

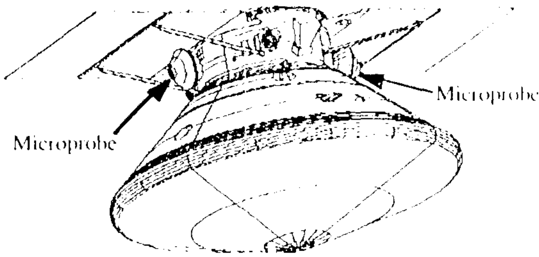
Second, the Microprobe Project is currently in negotiations with the Mars Global Surveyor Project to relay data from the probes to earth via the Mars Global Surveyor (MGS) Spacecraft. MGS, which launches for Mars in November,- 1996, includes a Mars Relay (MR) communication system which is also being used as a backup system to relay the 1998 Mars Lander spacecraft data if necessary. Thus the probes must be designed to be both compatible with unique MR communication features, and non-interfering with 1998 Mars lander data return.

Mission Overview

Launch and Cruise

The microprobes will be attached on the 1998 Mars Surveyor Lander spacecraft which is to be launched on a McDonnell Douglas Med-Lite (Delta II 7425 configuration). The 20 day launch window begins January 3, 1999. The piggy back configuration during the cruise (as shown in Figure 2: Basketball sized microprobes are mounted on the cruise stage (under the solar panels) of the 1998 Mars Surveyor Lander spacecraft (. The two microprobes are mounted the cruise stage, located under the cruise solar panels.

There are no electrical interfaces with the Lander or cruise stage, and thus there is no communication with the probes from installation on the pad until data relay after impact.



1998 Mars Surveyor Lander

Figure 2: Basketball sized microprobes are mounted on the cruise stage (under the solar panels) of the 1998 Mars Surveyor Lander spacecraft.

After an 11-month cruise, the integrated lander and microprobes will arrive at Mars near the southern summer solstice. The arrival parameters are designed to target the martian Polar Layered Terrain (PLT), which is of significant scientific interest due to its role as a reservoir for water and other volatiles on Mars. The landing region is shown in Figure 3. Superimposed on the image is a landing site trapezoid. The prime landing site is located at the northernmost boundary of the PLT deposits near 73 South, 210 West.

The bright south residual polar cap is offset from the geographic south pole. The boundary of the surrounding south polar layered deposits is outlined. The high-latitude landing site will provide unique opportunities to study the distribution and behavior of Martian volatiles, as well as aspects of Mars' past climate history.

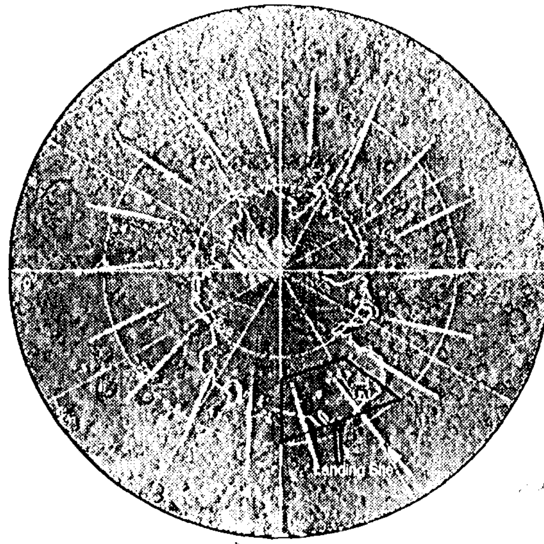


Figure 3: USGS Digital Terrain Model of the south polar region of Mars.

During arrival at Mars, the 1998 Mars Lander separates from its cruise ring approximately 8 minutes prior to Mars impact. The force of separation initiates mechanical pyros which in turn separate the microprobes from the cruise ring, approximately 1.5 seconds later. The microprobes are not spin stabilized upon release from the Lander cruise ring.

Entry, Descent and Impact (EDI)

Because the microprobes are separated with the aeroshell pointed orthogonally to the velocity vector and because the probes have no active control, attitude determination, propulsive system, or spin stabilization, they will not be able to control there orientation or tumble rate at entry. This would be a fatal condition for all other planetary mission designed so far, however it does not cause any problems for the microprobes. They have been designed to passively re-orient from almost any entry condition, including entering completely backward or with a small initial tumble rate.

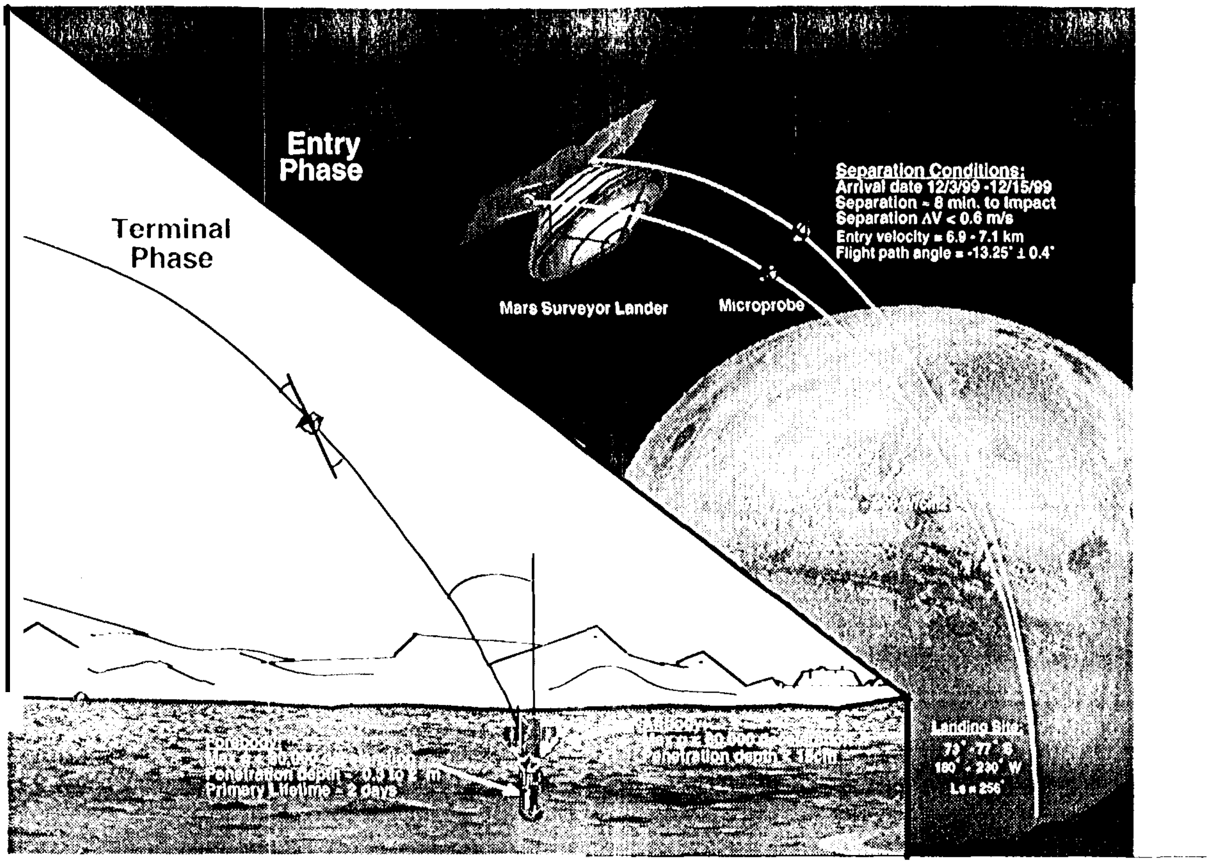


Figure -1: Cartoon of the It III I'J', Descent, and Im pact scenario.

The microprobe EDI system is single stage from atmospheric entry until impact. The non-erosive aeroshell uses advanced ablative material, being developed at NASA/AMES research center, that protects the entry vehicle from 300 W/cm2. The Material Phenolic Impregnated Ceramic Ablator (PICA) or Silicon Impregnated Reusable Ceramic Ablator (SIRCA) has provides a significant mass advantage over traditional aeroshell designs, and keeps the aerodynamic shape constant. The aeroshell will be carried to the surface, and will shatter upon impact leaving the penetrator aftbody clear for communications with the MGS spacecraft.

The microprobes are expected to hit the surface with an impact velocity of 160 to 200 m/s, an impact incidence angle $\leq 30°$, and an angle of attack $< 14°$. Upon impact, the penetrator will separate into a fore and aftbody that are connected via a cable system. The forebody is expected to penetrate to a depth of 0.3 to 2 m for soil types that vary from frozen-soil to very loose fine-grained soil, respectively. The forebody must also withstand a peak rigid body shock of up to 30,000 g's. The aftbody is designed to stay on the surface, and withstand a peak rigid body shock of < 80,000 g's.

An illustration of the microprobe EDI phase is given in Figure 4.

Operations

The forebody of the micropenetrator will include a microcontroller, power electronics, three impact accelerometers, one descent accelerometer, a subsurface sampling/water detection experiment and at least 2 temperature transducers. The forebody will weigh less than 900 g, and its isothermal temperature may range from 0 to -120° C depending on the thermal inertia of the soil at the landing site.

The aftbody will include two lithium batteries, a microtelecommunications system including an

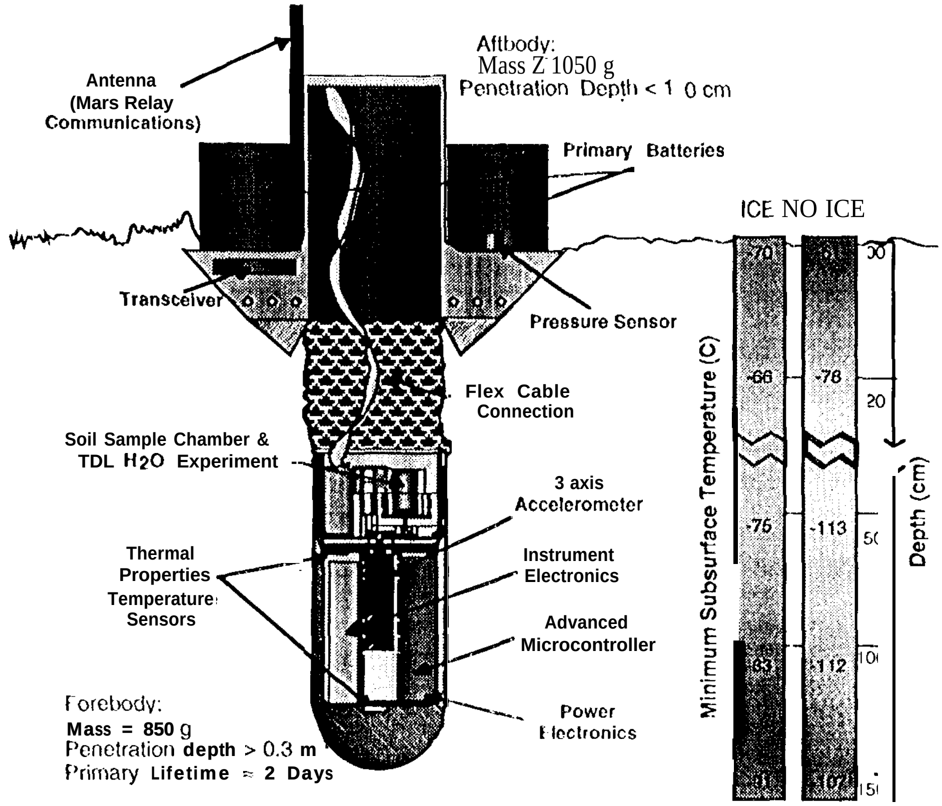


Figure S: Forebody and Aftbody in landed configuration.

antenna, a meteorological pressure sensor. The aftbody will weigh less than 1050 g, and its temperature will range from +0 to -78° C over one martian day. An overview of the post-impact probe configuration is given in Figure 3.

Upon impact, the deceleration force of the probe will deploy a UHF antenna and radiative fins on the aftbody. Soil will also fall into the rear of the forebody and be captured in a collection chamber. A checkout procedure will then be performed for verification of probe health.

To minimize peak power requirements, the sampling/water detection experiment will be performed within 30 minutes after impact, while the forebody is still warm from atmospheric entry. This experiment is designed to characterize subsurface soil composition by measuring the temperature at which water is released. This is accomplished by slowly heating a 100 mg soil sample in 10° C increments, and measuring water vapor content using a Tunable Diode Laser (TDL). Data collected will be filtered and stored in the microcontroller for multiple transmissions back to earth.

The probe will also collect temperature and pressure measurements every hour for the entire primary mission phase, which is the first two sols. Collection of these measurements will continue through a tentative secondary mission phase which will continue until the probe battery is depleted (approximately 12 additional days). The aftbody pressure sensor will provide meteorological data. Two temperature sensors mounted at opposite ends of the forebody will provide both soil conductance information and engineering status.

Data transmissions to the orbiting spacecraft are planned to take place 4 times during the first two sols, and once a week thereafter. Each UHF transmission session relays approximately 64 K bytes of data at an approximate. 7 Kbit/s rate.

The spacecraft batteries are designed to operate at least 50 hours and, as a goal, up to 2 weeks in the extreme martian thermal environment. This assumes a 2 W peak power for the one time 20 minute execution of the sampling/water detection experiment, a 0.5 W peak power for each data

downlink, and a 1 to 2 mW quiescent power for non-operating modes.

Technology Selection Process And Management Approach

The NMP organization includes Integrated Product Development Team (IPDTs) which are comprised of technology experts from industry, academia, NASA and other government centers. The six NMP IPDTs are listed below:

- Autonomy
- Microelectronic Systems
- Instrument Technologies and Architectures
- In situ Instruments and Microelectromechanical Systems (MEMS)
- Communication Systems
- Modular and Multifunctional Systems

Each IPDT has established a "road map", or phased technology development plan, which defines the current state of the technology, the technological goals for the 21st century, and milestones to achieve those technological goals.

For each NMP demonstration flight, IPDTs recommend specific technologies for flight validation. Each technology is then given a value for its long-term impact on science return and cost, the degree to which it is revolutionary in nature., and the risk reduction offered by flight validation. The Program Office, with inputs from the Flight Team, Science Working Group (SWG) and Science Advisory Team (SAT), then considers the total value of different combinations of proposed technologies along with the science value for that flight.

Programmatic and fiscal issues are also considered by the Program Office before a flight technology set is recommended to NASA Headquarters for approval. An overview of the NMP technology selection process is given in Figure 6.

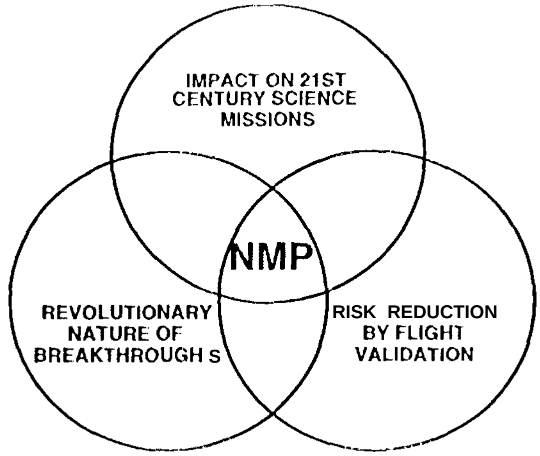


Figure 6: Technology selection processes.

After a technology is selected for flight, three "Fates" are negotiated between the IPDT and the Flight Team which ensure timely delivery of that technology for flight. The three gates which must be passed for flight acceptance are given below:

Gate 1	Technology Readiness Review
Gate 2	Key technology hardware/software demonstration
Gate 3	System hardware/software demonstration

The management approach for each technology is dependent on the consequence of that technology failing to pass a readiness gate. For the purposes of describing this approach, each technology is assigned a category ranking as shown in Table, 1.

Table 1: Technology Categories

Category	Role of Technology	Consequence of Failure to Pass Gate
I	Essential	Postpone or redefine mission
II	Fundamental	Substitute state-of-the-art technology
III	Enhancing	Fly without the technology

Category 1 technologies are given full flight team management oversight including status updates. Category II technologies are given minimal flight team supervision, with the three-gate schedule set to ensure that adequate time and resources are available to substitute an existing technology if necessary. Category III technologies are also given minimal flight team supervision, with the three-gate schedule set to ensure the technology is delivered for spacecraft integration and test only.

Flight Technologies

This section describes the technologies selected and approved for flight by NASA Headquarters for the Mars Microprobe Mission. It also describes why each technology is exciting for 21st century science.

Nell-lt-osi}fc "Single-Stage Entry Aeroshell

The microprobe will employ a single-stage-to-penetration entry system with no deployables, stages, active control or propulsion. This system will self-orient itself upon atmospheric entry prior to peak heating. The aeroshell will be made of a non-erosive heat shield material; possible candidates include a Phenolic Impregnated Ceramic Ablator (PICA) or Silicon Impregnated Reusable Ceramic Ablator (SIRCA). A small inside structure provides the necessary support for aft and forebody attachment. The 700 g aeroshell system will be designed to shatter upon impact.

Using a non-erosive material represents a mass savings of 50% or more over conventional thermal protection system technologies. It also minimizes aerothermal and aerodynamic analyses. Designing a passive re-orientation system simplifies the attachment and deployment strategy with the 1998 Mars Lander Spacecraft.

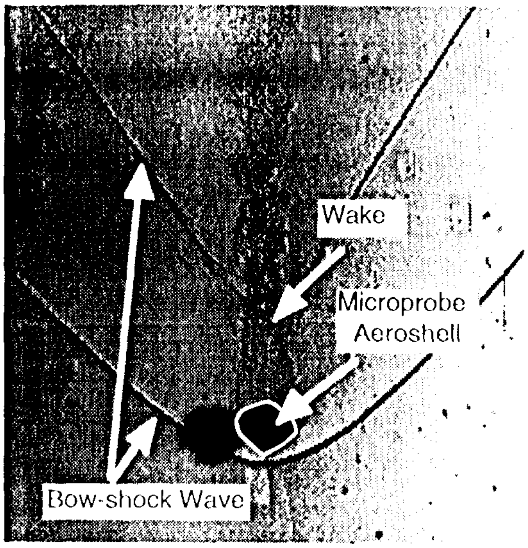


Figure 7: Image from a 1/4 Scale aer oshell test at Egland Air force Base, Flo (la. Aeroshe ll is traveling in the transonic flow region,

Telecommunications Microsubsystem with Programmable Transceiver

The probe telecommunications system will include a programmable transceiver. This development is exciting because of its multimission capability, which can be used for any moderate rate/range relay for both earth and space applications. The transceiver programmability extends to the data rate (1 kbps to 500 kbps), the modulation format (FSK or PSK), and the receive/transmit frequency (380 to 480 MHz). The microsubsystem represents a 100x reduction in mass over current spacecraft telecommunications subsystems (< 10 gm), and occupies a very small volume (< 8 cm3).

Figures 7, 8, 9, 10, 11, and 12 are not called out.

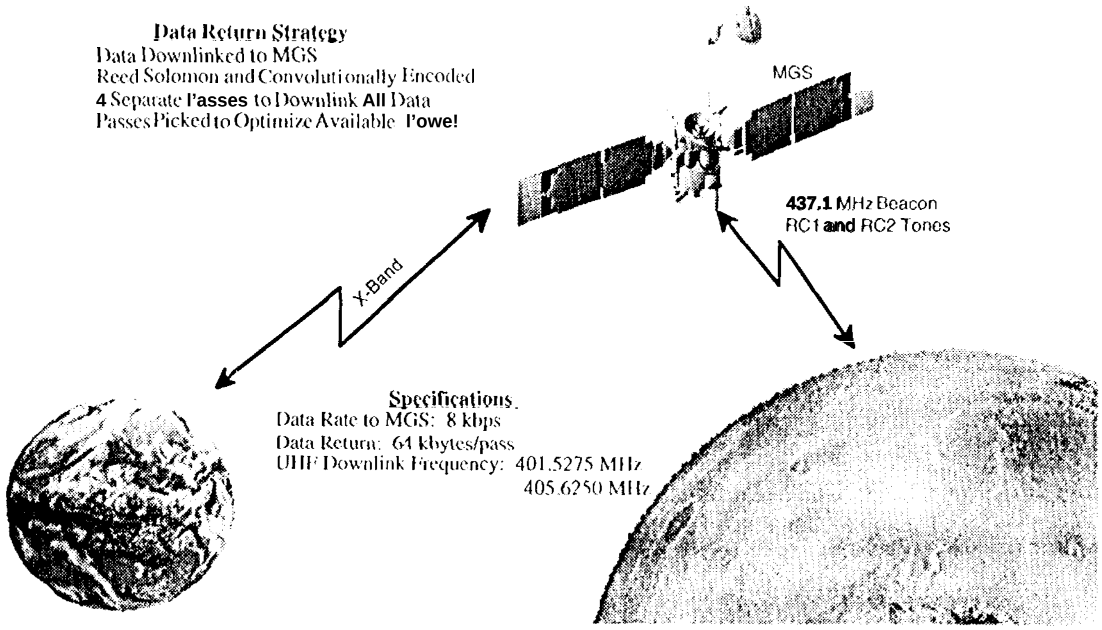


Figure 8: Microtelecommunications concept.

Ultra Low Temperature Lithium Primary Battery

Probably the most challenging aspect of the microprobe design is the requirement to survive the severe martian thermal environment. The batteries are likely to stay no warmer than -78° C. To survive this extreme, both lithium-thionyl chloride and lithium-carbon monofluoride battery chemistries are being considered. The microprobe primary battery will be designed for a 6-14 V range and a 3 year shelf life. The battery will also have to withstand a worst case 80,000 g rigid body shock environment.

Low temperature battery technology is extremely useful for Mars landers and rovers as well as other deep space missions. It also has commercial, DOD, and DOE applications.

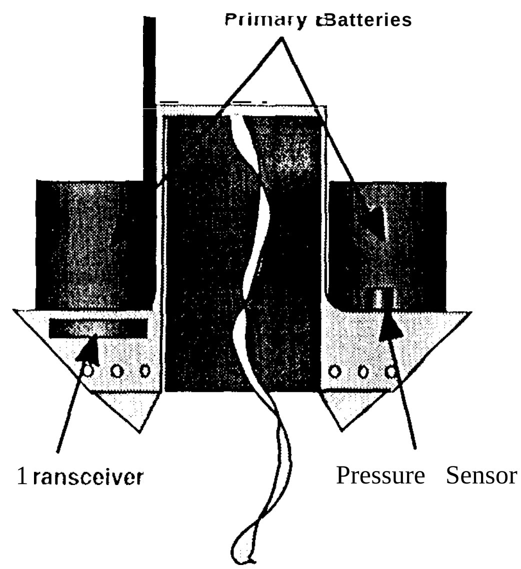


Figure 9: Aftbody technology accommodation.

Power Microelectronics: Mixed Digital and Analog ASICs

The microprobe power control, regulation, and distribution will be operated via microelectronics that use mixed digital/analog ASICs. Mixed digital/analog ASICs represent an exciting extension of the miniaturization achieved by the digital electronics industry in the last quarter century. This power system will use CMOS technology with very low temperature capabilities. This technology is useful for a suite of applications including any high density sensor, instrument, or assembly.

Microcontroller

The microprobes will include an 8051-based data acquisition and control system with modest data processing capability. This microcontroller is an 8 bit processor with 64K RAM and 128K EEPROM. The system is designed for both very low power (< 50 mW at 1MHz, 1mW sleep mode) and small volume and mass (< 8 cc, 30-90" g). The microcontroller system will also include an internal 12-bit 16 channel analog to digital converter (ADC). Because this system has multifunctional applications, it will be developed and funded by a consortium of government and industry participants. Potential applications for this microcontroller include any small system or instrument including microprobes, actuators, and health and status monitors.'

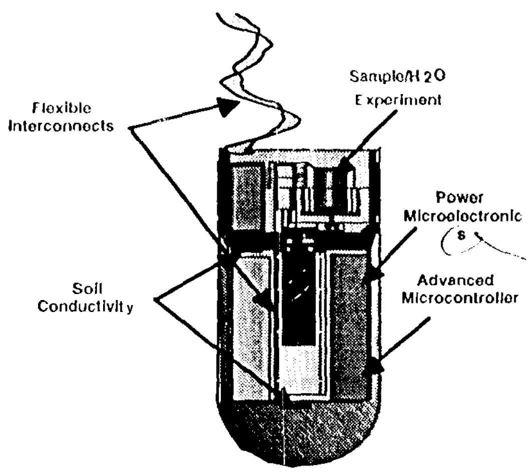


Figure 10: Forebody technology accommodation.

Flexible Interconnects for System Cabling

The microprobe's high shock and vibration environment presents a challenge for system-level packaging. One packaging approach that will be demonstrated on this mission is flexible. interconnects for system-level cabling, Flex is a Kapton based multilayer circuit carrier and interconnect technology. The flex circuits used for the penetrator will include. electrical interconnects between Kapton layers which are formed with a patented anisotropic bonding material made of thermal glue matrix with embedded solder balls. This bonding technique can withstand temperature extremes and can be used to attach surface mount parts using reflow solder. This approach provides unparalleled bending flexibility and oxidation resistance, and is applicable to any micro sensor, assembly, or instrument.

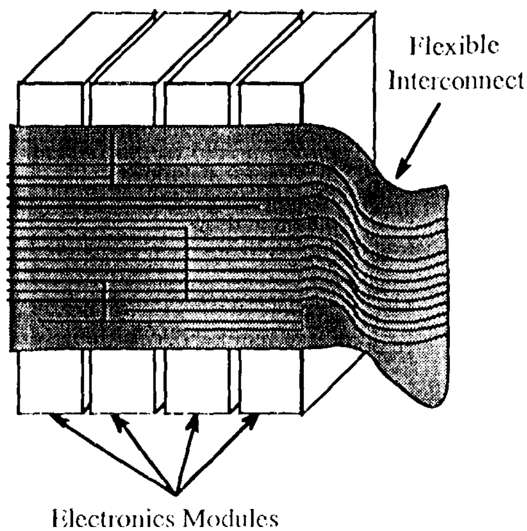


Figure 11: Flexible Interconnect for system cabling.

Subsurface Sampling/Water Detection Experiment

A subsurface sampling/water detection instrument has been chosen as the primary science instrument for the microprobes. The primary purpose of this instrument is to demonstrate subsurface sampling capability. This sampling is accomplished as soil fails passively into the back end of the forebody and into a small collection chamber upon impact. The secondary purpose of this experiment is to detect ice and/or absorbed water in the soil collected, with a goal of identifying hydrated minerals. This is accomplished by increasing the temperature of the sample in a stepwise fashion and measuring the water detected and sample temperature at each step. Water detection is accomplished via a micro Tunable Diode Laser (TDL) spectrometer.

Including this instrument On the Microprobe Mission demonstrates penetrator-based subsurface sample collection and geochemistry capability. This experiment can be extended in future missions to include quantitative analysis of water and other volatiles, which addresses high science priorities for Mars and other planets.

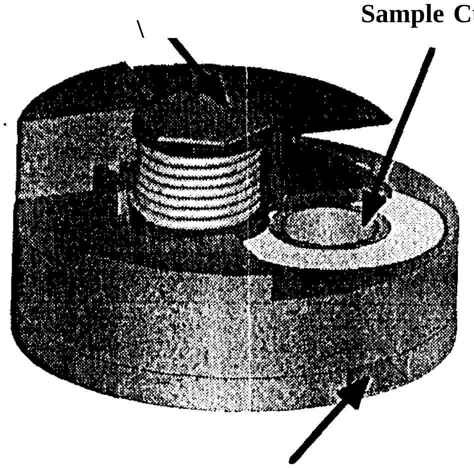


Figure 12: Soil sample acquisition and water experiment drawing.

Meteorological High-g Micropressure Sensor

As an important step toward validating a microprobe meteorological network, this mission will include a pressure sensor on the probe aft-body. Demonstrating a meteorological network is of primary science interest for Mars, Venus and Titan.

A silicon capacitive micromechanical pressure transducer will be used in conjunction with a miniaturized hybrid/high-g electronic package. The 20 gm sensor will measure an absolute pressure range of O -25 mbar over an operating range **of -90° C to +50° C.**

Soil Conductivity High-g Temperature Sensor

Two temperature sensors will be mounted at opposite ends of the penetrator forebody to determine soil conductivity from the penetrator cooling curve after "impact. 'This experiment validates a mass and power efficient approach to determining thermal properties over traditional methods, in that the surrounding soil does not need to be heated to obtain a temperature vs. time profile. This experiment also represents an initial step towards a planetary heat flow experiment which is of scientific interest for determining the thermal evolution of the planets.

Accelerometers

Although penetrator accelerometers are not a "new technology" per se, the application of accelerometers and penetrators for deep space missions has not been demonstrated to date. At least three piezoresistive or piezoelectric accelerometers will be mounted in the Mars microprobes and will serve two purposes. First, accelerometer data will provide verification of martian soil penetration, and characterizes entry conditions (e.g. depth of penetration and acceleration at impact) for technology validations. Second, the accelerometers will provide information regarding geological stratification; possibly including the depth to an ice layer that is predicted to occur near the surface and will provide information on climate changes on Mars.

High-g Testing

The microprobe has a large number of design challenges all of which are greatly compounded by the high deceleration environment during impact. These impact energies are difficult to reproduce in a laboratory environment. Analysis tools are immature. and very time consuming with results that are hard to utilize. Therefore, early on the NMP team started an extensive testing program to verify concepts and eventually qualify the. flight design.

Several test methods have been used. The majority of the early testing utilized airborne drops, shown in Figure 13. The team contracted with a sky diving organization in California City. This type of testing provided an inexpensive mentioned to test concepts, where multiple units can be "dropped" in a single pass. The largest difficulty in this testing method was locating the test articles after the test, The test area could cover a radius of several kilometers.

Figure 13: NMI' engineers prepare several test probes from airborne drops in the Mojave desert.

Air gun testing is an other method in which all of the testing parameters arc controlled very precisely. These tests cost a great deal more than airborne test, but yield a great more results. The velocity of the probe is measured by high speed photography. A test firing can be seen in Figure 14.

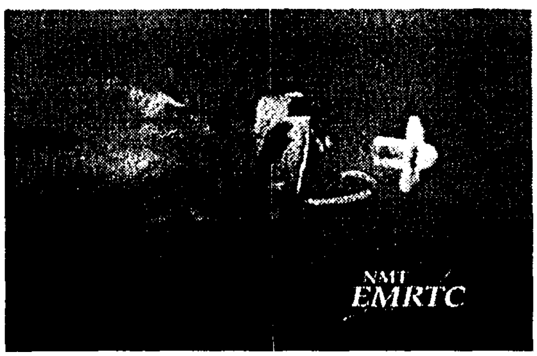


Figure 14: High speed photography of the aft and forebod y traveling at 160 m/s.

Summary

The New Millennium's Mars Microprobe Mission provides an exciting demonstration of a suite. of new technologies for deep space surface and subsurface scince networks. Networks have been identified as a key scientific objective for the exploration of dynamic planetary systems. Technologies selected for flight will be developed by a team of JPL, industry, academic and other government agency participants. As part of the New Millennium Program, the Mars Microprobe Project will also explore new management and engineering approaches toward developing inexpensive, rapid development, planetary spacecraft.

Acknowledgments

This effort represents the work of the. Mars Microprobe Flight Team and the New Millennium Integrated Product Development Teams. The work described here was carried out try the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration,

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